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Compact Dual-Polarized Antenna for Dual-Band Full-Duplex Base Station Applications

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ABSTRACT A compact single-radiator microstrip patch antenna with highly integrated duplexing and filtering functions is proposed for dual-band dual-polarized (DBDP) base-station applications, and the center frequency ratio of the upper and the lower operation band is just 1.14. The single radiation patch with four high isolation channels is oriented along the 45° diagonal of the ground plane to achieve the ±45° dual linearly polarizations (LP) at each of the two operation bands. For each polarization, the dual-band full-duplex characteristic is obtained by conceiving the strong mutual coupling between the combined resonator and the radiation path, and the mutual coupling then couples to two groups of resonator-based channels with different working frequencies. Therefore, high channel isolation is achieved, without resorting extra decoupling structures. Moreover, the mutual coupling of each resonator-based channel can help to improve its corresponding operation band and produce the third-order filtering feature, leading to enhancement of the full-duplex characteristic for the proposed antenna. Such a single-patch four-port DBDP antenna could significantly reduce the complexity and volume of the RF frontend of the base station. The removal of the bandpass filters and duplexers in the design could also reduce the potential cost of the RF frontend. The measured results agree well with the simulations, showing an excellent performance in terms of bandwidths, channel isolations, polarization isolations, radiation patterns, and gains.

INDEX TERMS Base-station, dual-band, duplexing, dual-polarization, filtering, microstrip antenna.

I. INTRODUCTION

Mobile communication systems have experienced unprecedented rapid development in the past years. The base-station (BS) antennas with wideband or multiband are widely demanded to support different wireless applications. The BS antennas are also required to have the dual linearly polarizations (LPs) to reduce the multipath fading effects while increasing the channel capacity [1], [2].Usually, the dual-polarized BS antennas with broad impedance and radiation bandwidths, including magneto-electric dipole antennas [3]–[6] and cross-dipole antennas with different shapes [7]–[10], are employed to cover different frequency bands of the communication systems. Although very wide bandwidths over 45% are achieved, these antennas require the reflectors to prevent the backwards radiation, and leading to increasement of the antenna system volume.

In many contexts that the multiple frequency bands are closely located, such as Digital Cellular System (DCS, 1710-1880 MHz) and Wideband Code Division Multiple Access (WCDMA, 1920-2170 MHz), extra duplexers or multiplexers with good isolation are always required to separate the different channels. That not only increases the volume and complexity of the RF frontend but also limit the flexibility of individually controlling the down-tilt of each operation band [11]. One of the feasible solutions is to place two antenna arrays with different operation band side-by-side [12] or interlaced [13], [14]. However, additional decoupling networks are usually required for improving the channel isolation, and that will result in the deterioration of the radiation performance. The mutual coupling between the two bands can also be significantly reduced by the property

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of good out-of-band rejection of the filtering antenna elements [15]. This method could reduce the complexity and size of the antenna by removing the decoupling networks, but the size reduction is limited, because two separate arrays are required. In [16], a dual-band dual-polarized filtering antenna with shared aperture is proposed. However, the two operation bands are widely separated in frequency and share the same feeding network, the antenna thus is not suitable for full-duplex operations.

Recently, the co-design of multi-functional devices provides a feasible solution to size reduction of RF frontends while providing the improved performance. The integrated filtering antennas with improved bandwidth [17], good frequency selectivity [18], [19], perfect harmonic suppression [20] and wide dual-band [21] have been reported. Dual-band filtering antennas with integrated duplexing function were investigated [22], [23], both the antenna [22] and the Antenna-II [23] used a single radiation patch to support the uplink and downlink transmission simultaneously, while providing an excellent channel isolation. However, the two antennas have the same polarization for their two operation bands, and that is not useful to reduce the interferences between the uplink and downlink channels.

In this paper, a dual-band dual-polarized (DBDP) microstrip antenna at DCS/WCDMA bands with integrated duplexing and filtering functions is proposed for the 1st time. The center frequency ratio of the upper and the lower operation band is just 1.14. Different from the traditional methods, the two bands for each polarization are realized simultaneously by a single radiation element, leading to the reduction of the antenna size. Moreover, due to the integrated duplexers, very good channel and polarization isolations are achieved. The antenna also exhibits flat in-band gain, stable radiation pattern, and excellent out-of-band rejection.

II. ANTENNA DESIGN

A. SPECIFICATIONS

Table 1 summaries the specifications and design targets of this work. The antenna works at DCS and WCDMA bands simultaneously, and each band has the ±45° dual LPs. The bandwidths of the DCS and WCDMA are 160 and 250 MHz, respectively. The isolations between the two channels/bands of each polarization as well as the polarization isolation of each band are required to be over 20 dB. The other important requirement is that the overall size of the dual-band radiator should be constrained in 0.5 λ × 0.5λ @ 1800 MHz or 0.55λ × 0.55λ @ 2045 MHz. Moreover, for both the two bands, the H-plane beam-widths of the antenna are required to be 65°± 5° and the cross polarization discrimination (XPD) should be over 20 dB.

TABLE 1. Specifications of the DBDP duplexing antenna.

Frequency band	DCS-band	WCDMA-band
Centre frequency	1800MHz	2045MHz
Polarization	Dual linearly polarizations	
Impedance bandwidth	1720-1880 MHz	1920-2170 MHz
Channel isolation	20 dB	
Polarization isolation	20 dB	
Radiator size	0.5 λ × 0.5 λ	0.55 λ × 0.55 λ
Beam-width	65°± 5°	65° ± 5°
discrimination (XPD)	20 dB	

B. CONFIGURATION

Fig. 1 shows the configuration of the proposed DBDP duplexing filtering antenna for DCS/WCDMA base station applications. The antenna consists of two stacked substrates and a foam spacer between them, as shown in Fig. 1(a). The radiation element is a square patch, which is printed on the top layer of the upper substrate. The patch is rotated by 45° to enable the dual linearly polarizations radiations in ±45° for each of the two operation bands. The copper ground plane is printed on the top layer of the lower substrate. In the ground plane, as shown in Fig. 1(b), a H-shaped and a U-shaped slots are cut for coupling the electromagnetic energy from the feeds to the square patch, and support the radiation in +45° and −45°, respectively. These two slots are symmetrical regarding the −45° diagonal line of the ground plane. On the bottom layer of the lower substrate, there are four groups of split ring resonators (SRRs), leading to four resonator-based filtering channels, which and the corresponding four microstrip feed lines are arranged in a compact area, as shown in Fig. 1(c). Such a compact arrangement is useful for potential large array antenna designs. The channel-1, 2, 3 and 4 operate at low-band +45° polarization, high-band +45° polarization, low-band −45° polarization and high-band −45° polarization, respectively. It should be noted that the channel 1 and 2 share the H-shaped slot, whereas channel 3 and 4 share the U-shaped slot. The operation principle for implementing the dual-band duplexing functions of each polarization will be detailed in Section II-C later. RO 4003C substrate with the permittivity of 3.55 and thickness of 0.813 mm is used in this work. All simulations were performed using the high frequency structural simulator (HFSS 17) and the optimized values are also given in Table 2.

TABLE 2. Optimized dimensions of the proposed antenna: (MM).

OPTIMIZED DIMENSIONS OF THE PROPOSED ANTENNA: (MM)							
L_{patch}	H_{foam}	L_{GND}	L_{s1}	L_{s2}	L_{s3}	L_{s4}	W_f
54.5	6	120	25	10.5	21	5.2	1.8
L_{01}	L_{02}	L_{03}	L_{11}	L_{12}	L_{13}	L_{21}	L_{22}
10	14	2.5	14	14	5.9	11	14
L_{23}	L_{31}	L_{32}	L_{33}	L_{41}	L_{42}	L_{43}	
2.9	7	21	3	7	18	2.5	

C. DUAL-BAND DUPLEXING IMPLEMENTATION

To illustrate the mechanism of achieving the dual-band duplexing functions in both +45° and −45° polarizations,

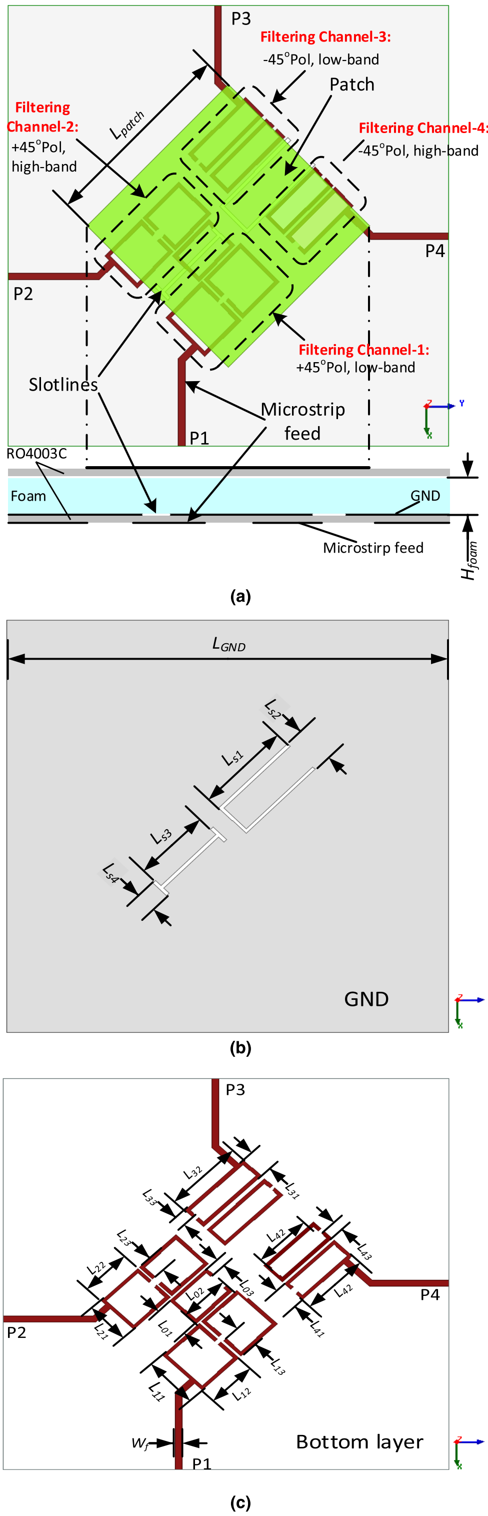

FIGURE 1. Configuration of the proposed DBDP duplexing filtering antenna: (a) explored and side view, (b) ground plane with slot lines, (c) bottom layer with resonator-based filtering channels.

the antenna in Fig. 1 is decomposed into two antenna prototypes, as shown in Fig. 2. The first prototype, denoted as Ant-I, has LP in +45°, as the arrow shown Fig. 2(a). The other one has LP in −45° and is named Ant-II, as shown in Fig. 2(b). Both Ant-I and Ant-II have two ports and two channels, and they are roughly symmetrical along the ±45° diagonal lines of the ground. In this work, Port 1 and 3 operate at the low-band (DCS-band), whereas Port 2 and 4 operate at the high-band (WCDMA). As can be observed, each port has the 2nd-order frequency selective channel, resulting from the two coupled SRRs.

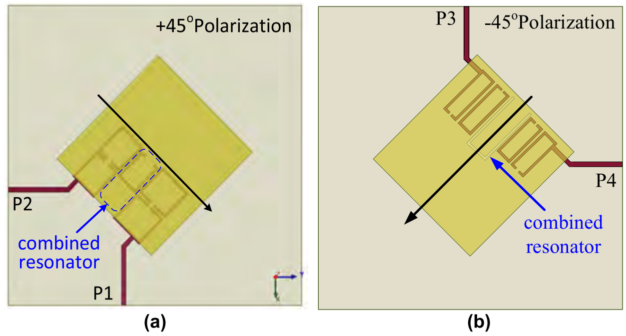

FIGURE 2. Configurations of the two discomposed dual-band duplexing antennas in two orthogonal polarizations: (a) Ant-I, +45° polarization, (b)Ant-II, −45° polarization.

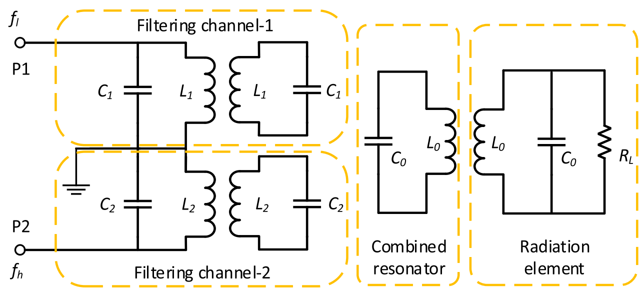

FIGURE 3. Equivalent circuit of the dual-band duplexing antennas for both polarizations.

The implementation of the dual-band duplexing capacities at the both polarizations can be explained by an equivalent circuit, as shown in Fig. 3. The radiation patch is modeled using a shunt *RLC* resonator, which is followed a combined resonator, and the combined resonator is modeled by a shunt *LC* resonator. These two resonators are intensively coupled, producing two separate resonant frequencies f_1 and f_2. Taking Ant-I as an example, these two resonant frequencies can be respectively coupled to the two resonator-based filtering channel-1 and 2 directly, thanks for the symmetry of the antenna structure, and thus two transmission channels with different working frequencies are produced. Due to the different resonant frequencies, a good isolation between the two channels can be realized.

The production of the two separate resonant frequencies f_1 and f_2 are achieved by conceiving the strong mutual coupling between the combined resonator and radiation element. The strong mutual coupling is realized by coupling the combined SRR (center one, as shown in Fig 1(a) or Fig.2(a)) to the radiation patch through an H-shaped slot for Ant-I, but for

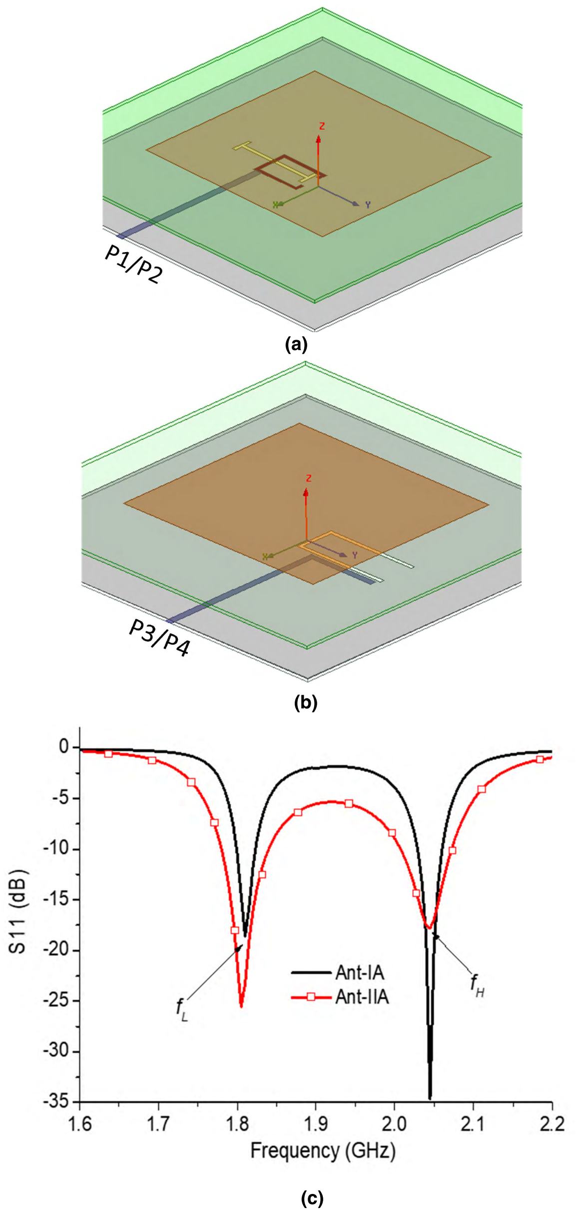

FIGURE 4. Configurations of the two dual-band microstrip antennas in two orthogonal polarizations: (a) Ant-IA, X-polarization, (b)Ant-IIA, Y-polarization, (c) simulated S11 of the two antennas.

Ant-II, that is achieved by inserting the combined U-shaped slot resonator in the ground, which is stacked and coupled with the radiation patch. To illustrate this, Ant-IA composed of the combined SRR and radiation patch, and Ant-IIA consisting of the combined U-shaped slot and the radiation patch, are shown in Figs. 4(a) and 4(b), respectively. Fig. 4(c) shows the simulated $S11$ of Ant-IA and Ant-IIA. As can be seen, both the two antennas have two resonant frequencies at about 1.8 (f_L or f_1) and 2.05 GHz (f_H or f_2), respectively. These two frequencies are then served as the center frequencies of the DCS and WCDMA bands, respectively.

For both the two antennas, the two resonant frequencies f_L and f_H can be adjusted by changing the coupling strength between their corresponding combined resonator and radiation patch. For Ant-IA, this coupling strength can be controlled by changing the length L_{s3} of the coupling H-shaped slot, as shown in Fig.4(a). As can be seen from Fig. 5(a), the higher frequency f_H slightly increases whereas the lower frequency f_L decreases dramatically with increasing L_{s3}. For Ant-IIA, the coupling strength can be controlled by adjusting the thickness H_{foam} of the foam. As the thickness of the foam increases, indicating a weak coupling between the U-shaped slot resonator and the radiation patch, the lower resonant frequency f_L slightly increases and the higher frequency f_H significantly reduced, as shown in Fig. 5(b). Therefore, the two center frequencies of the two operation bands for both polarizations (Ant-IA used for +45°, and Ant-IA used for −45° polarizations) can be controled, and the dirsierd center frequencies can be obtained easily.

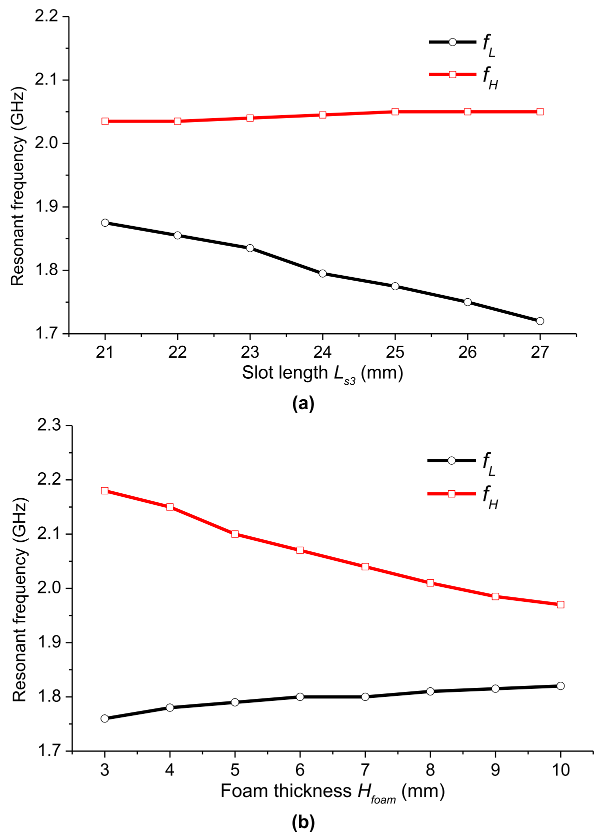

FIGURE 5. (a) Two resonant frequencies of the Ant-IA with different lengths of the coupling H-shaped slot L_{s3}; (b)Resonant frequencies of the Ant-IIA with different thickness of the foam H_{foam}.

To achieve the dual-port duplexing and filtering functions, the Ant-I and its original prototype Ant-IA are compared and discussed. As can be seen in Fig. 6, the two bandwidths of the Ant-IA are very limited. When the two filtering channels are integrated by Ant-I, the Port 1 has a working band at around 1.8 GHz with the improved bandwidth and 3rd-order filtering features. For Port 1 excited, however, the higher band is canceled due to the frequency selectivity of the channel-1. When the Port 2 is excited, in contrast, the higher operation

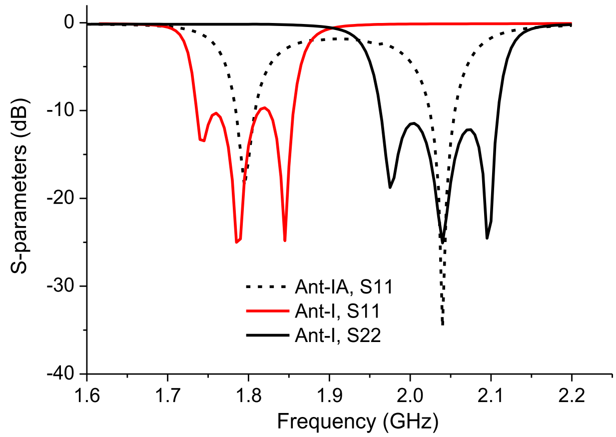

FIGURE 6. Simulated S-parameters of the Ant-I and Ant-IA.

band with the improved bandwidth and 3rd-order filtering performance is realized, but the lower band is canceled due to the frequency selectivity of the channel-2. As a result, the dual-band duplexing and filtering characteristics of Ant-I are realized in the same +45° polarization.

Similarly, the duplexing and filtering characteristics in the −45° polarization can be realized by Ant-II. For the proposed antenna shown in Fig.1, Ant-I and Ant-II are integrated together, so a compact dual-band dual-polarized antenna with duplexing and filtering functions is achieved.

D. CURRENT DISTRIBUTION

Fig. 7 shows the simulated current distributions of the proposed DBDP duplexing antenna with different ports excited. When Port 1 is excited at 1.8 GHz, as shown in Fig. 7(a), currents are mainly distributed on the SRRs and the feed line of the channel-1 as well as the combined resonator at the center. However, the currents on the other channels/feeds are dramatically reduced due to the high channel isolations and the orthogonal polarizations. On the radiation patch, the current flows along the +45° orientation, indicating a radiation in +45° polarization. When Port 2 is excited at 2.06 GHz, the SRRs and feed line of the channel-2 and the combined resonator at the center have strong currents, whereas currents distributed on the channel-1, 3 and 4 are inactive. Consistently, the current distribution of the radiation patch is also in +45° orientation for this case, showing that a radiation in +45° polarization is also produced by Port 2.

For the channel-3 and 4, similarly current distribution can be observed, as shown in Figs. 7(c) and 7(d), but the currents on the radiation patch flow along −45° orientation both for 1.8 GHz and 2.06 GHz, indicating the radiations in −45° polarization are obtained.

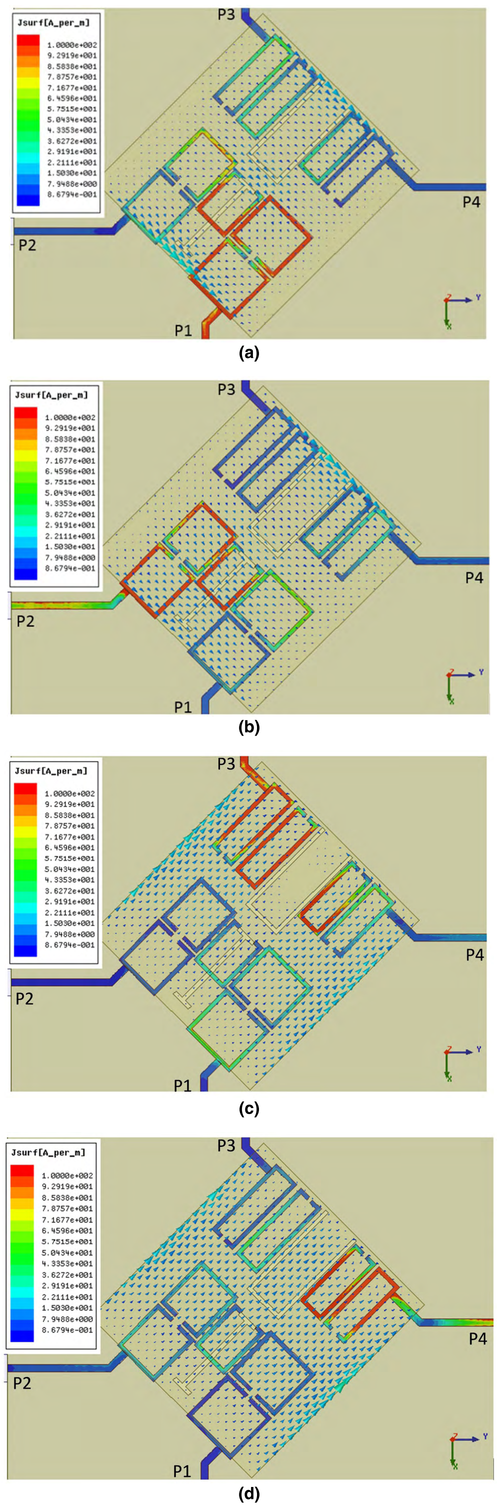

FIGURE 7. Current distribution of the dual-band dual-polarized duplexing antenna: (a) Port 1 is excited, 1.8 GHz, +45°-Pol, (b) Port 2 is excited, 2.06 GHz, +45°-Pol, (c) Port 3 is excited, 1.8 GHz, −45°-Pol, (d) Port 4 is excited, 2.06 GHz, −45°-Pol.

III. RESULTS AND DISCUSSION

The proposed DBDP duplexing filtering antenna was prototyped and shown in Fig. 8. Fig. 9 shows the simulated and measured S-parameters of the proposed DBDP antenna working in +45° polarization (Port 1 and 2 are excited). As can be observed, the measured results agree very well with the simulations. When Port 1 is excited, the antenna shows an impedance bandwidth of 1730-1860 MHz for

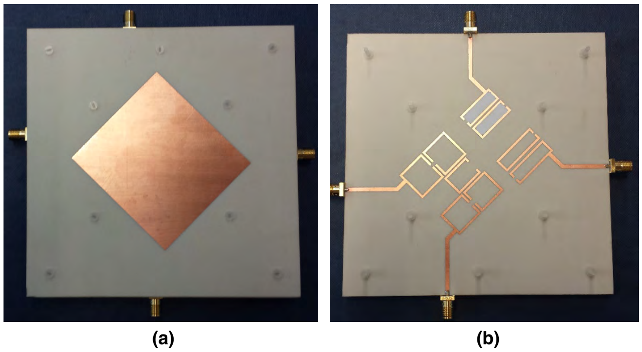

FIGURE 8. Prototype of the proposed DBDP duplexing filtering antenna: (a) front view, (b) back view.

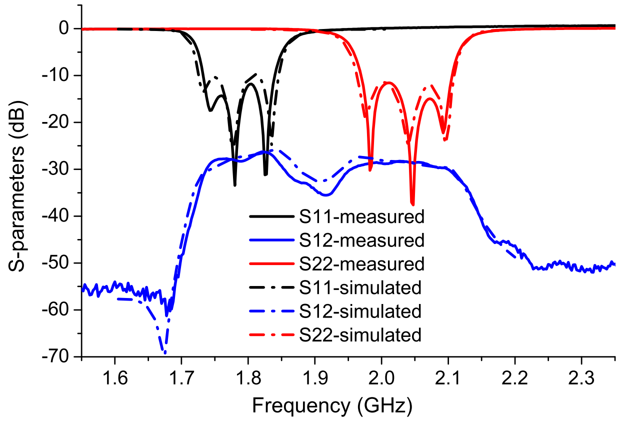

FIGURE 9. Simulated and measured S-parameters of the antenna in +45° polarization (Port 1 and 2 are excited).

DCS application. When Port 2 is excited, however, the antenna has another impedance bandwidth of 1960-2120 MHz for WCDMA application. Both the two operation bands exhibit the 3rd-order filtering characteristics with good bandwidth and high frequency selectivity. The antenna also shows an excellent isolation of over 26 dB between the two channels, and that is indicated by the curve of $S12$.

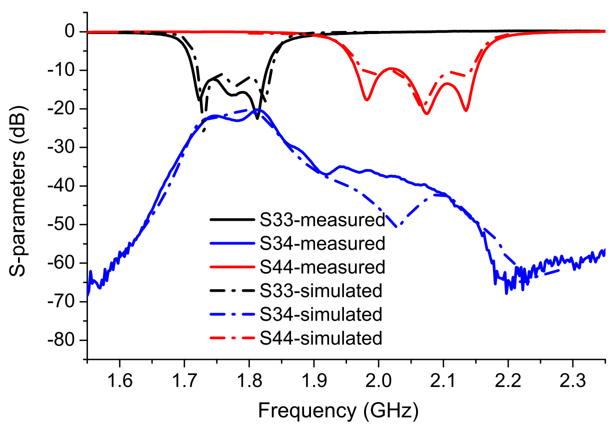

FIGURE 10. Simulated and measured S-parameters of the antenna in −45° polarization (Port 3 and 4 are excited).

Fig. 10 shows the simulated and measured S-parameters of the proposed antenna working in −45° polarization (Port 3 and 4 are excited). Similarly, the antenna has a low-band from 1710 to 1830 MHz when Port 3 is excited, and a high-band from 1960 to 2160 MHz when Port 4 is excited. Both the two frequency bands exhibit the 3rd-order filtering features with good frequency selectivity. The measured channel isolations are over 21 dB and 35 dB at the low- and high-band, respectively. The minor discrepancies between the simulations and the measurements are attributed to the manufacturing tolerance.

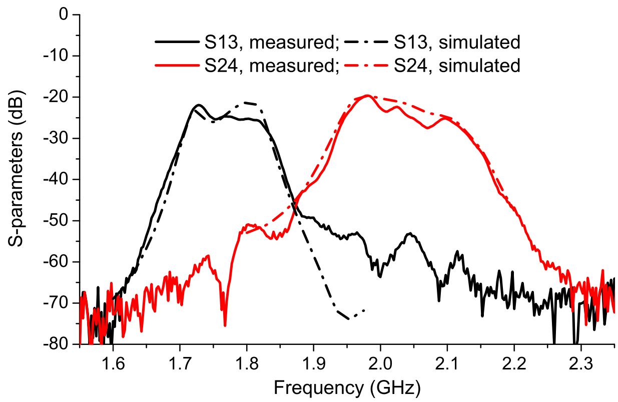

FIGURE 11. Simulated and measured mutual couplings between the two polarizations.

For the dual-polarization antenna, the isolation between the ±45° orthogonal polarizations should also be tested. Fig. 11 shows the simulated and measured S-parameters of both the two bands. As can be seen, the measured results agree reasonably well with the simulations. At the low-band, the isolation between the different polarizations (Port 1 and 3) is over 21 dB. At the high-band, the isolation between the orthogonal polarizations (Port 2 and 4) is higher than 20 dB. All these results show that the antenna has excellent isolations between the different polarizations for the low- and high-band.

When Port 1 and 3 of the proposed DBDP duplexing antenna are excited individually, the simulated and measured normalized radiation patterns at the central frequency 1800 MHz of DCS-band are shown in Fig. 12. With broadside radiation in both E- and H-planes, the measured patterns agree well with the simulations. When Port 1 is excited, the measured 3-dB beam-width of E-plane ($\varphi = +45°$) is 62°, and the XPD in broadside direction is about 19 dB. In H-plane ($\varphi = -45°$), the measured 3-dB beam-width is about 72°, and the XPD in broadside direction is 19 dB. The slots etched on the ground plane will results some energy radiated in the direction of back lobe, and no metallic reflector is used in the proposed design, so there is inferior backward radiation for the simulations. However, the measured backward radiation patterns are quite trivial, and that is because the measurement instruments located in the direction of the back lobe can hinder the energy in radiation backward. When Port 3 is excited, similar radiation patterns with Port 1 excited

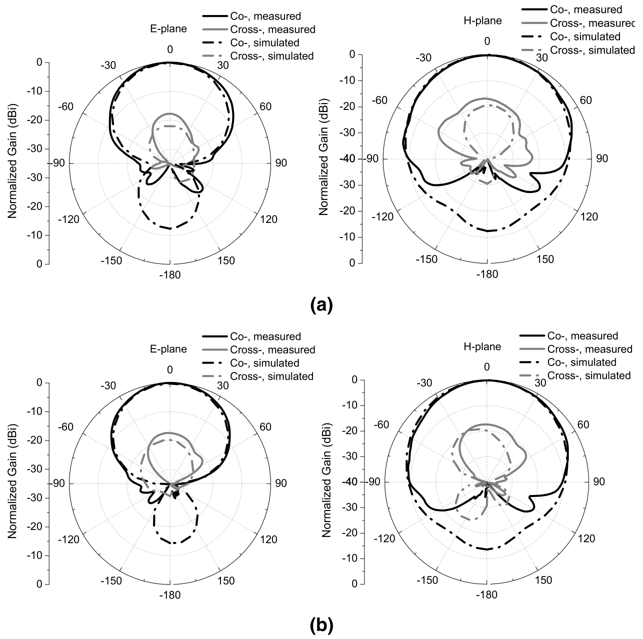

FIGURE 12. Simulated and measured normalized radiation patterns of the DBDP duplexing antenna at 1800 MHz: (a) Port 1 is excited, (b) Port 3 is excited.

can be observed, except that the E-plane is $\varphi = -45^\circ$ plane and H-plane is $\varphi = +45^\circ$ plane.

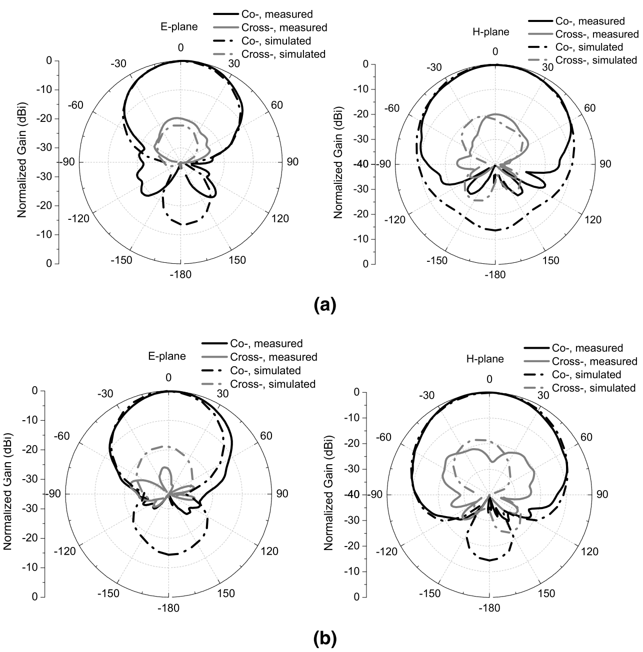

FIGURE 13. Simulated and measured normalized radiation patterns of the DBDP duplexing antenna at 2060 MHz: (a) Port 2 is excited, (b) Port 4 is excited.

As discussed above, Port 2 and Port 1 have the same $+45^\circ$ polarization characteristics, whereas Port 4 and Port 3 have the consistent -45° polarization characteristics. When Port 2 is excited, E- and H-planes are $\varphi = +45^\circ$ plane and $\varphi = -45^\circ$ plane, respectively. When Port 4 is excited, E-plane is $\varphi = -45^\circ$ plane, and H-plane is $\varphi = +45^\circ$ plane. Fig. 13 shows the simulated and measured normalized radiation patterns at the central frequency 2060 MHz of WCDMA when Port 2 and 4 are excited individually. A good agreement between the measured and simulated results also is achieved, showing the radiations in broadside direction. For the $\pm 45^\circ$ polarizations, the radiation patterns are correspondingly consistent, the measured 3-dB beam-widths of the E- and H-plane patterns are around 61° and 72°, respectively, and the measured XPD are over 20 dB for both E- and H-planes.

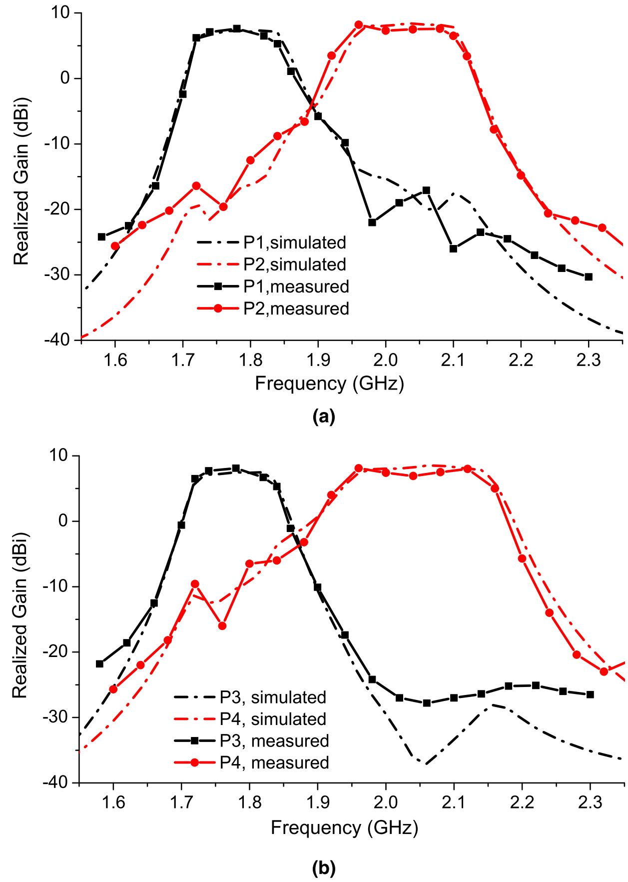

FIGURE 14. Simulated and measured realized gains of the dual-band duplexing filtering antenna: (a) +45° polarization, (b) −45° polarization.

Fig. 14 shows the simulated and measured realized gains of the proposed DBDP duplexing antenna. The measured and simulated results are in a good agreement. When port 1 with $+45^\circ$ polarization is excited, the proposed antenna has a flat gain of 7 dBi from 1.72 to 1.86 GHz, as shown in Fig. 14(a). The gain rapidly decreases by more than 20 dB as the frequency shifts away from the operation band, leading to an excellent filtering performance. When port 2 with $+45^\circ$ polarization is excited, a flat gain of 7.2 dBi is obtained within the band of 1.95 - 2.12 GHz, the gain is reduced to below -10 dBi for the frequencies out of the operation band, and a desired filtering performance also can be obtained. The inter-channel gains at 1.8 GHz and 2.06 GHz are around

TABLE 3. Comparison with other dual-band LP antennas.

Antenna		Radiator number	Dual-band Channels	LP property		Frequency ratio (f_H/ f_L)	Filtering feature	Systematic integration
				Lower band	High band			
[13]		4	Separated	±45°	±45°	1.29	Good	Low
[14]		4	Separated	±45°	±45°	1.32	No	Low
[16]		4	Combined	X-axis	Y-axis	1.90	Fair	Low
[23]	Antenna-I	1	Combined	X/Y-axis	X/Y-axis	1.22	Good	Fair
[23]	Antenna-II	1	Separated	X-axis	X-axis	1.38	Good	Fair
This work		1	Separated	±45°	±45°	1.14	Good	High

−10 and −18 dBi, respectively, indicating a good isolation between the two channels. On the other hand, the high realized gain is benefit from the good channel and polarization isolations of the proposed antenna without resorting extra decoupling structures. The discrepancies between the simulations and measurements are attributed to the test tolerance. Fig. 14(b) shows the simulated and measured gains when Port 3 and 4 are excited individually, and the proposed antenna works in −45° polarization for the two cases. Similar results as that in +45° polarization shown in Fig.14(a) are achieved. The inter-channel gains at 1.8 GHz and 2.06 GHz are below −8 dBi and −25 dBi, respectively.

Table 3 compares the proposed dual-band patch antenna with the other four reported dual-band antennas [13], [14], [16] and [23]. For all the antennas, f_L and f_H are served as the center frequencies for the lower and the higher bands, respectively. The comparison focuses on the number of antenna radiators, the channels and the LP property for the two operation bands, frequency ratio (f_H/f_L), filtering characteristic, and systematic integration level. This comparison shows that just the proposed antenna and the Antenna-I [23] employ a single radiation element but achieve the dual-band operation and orthogonal LP property characteristic of each operation band. However, the two operation bands of Antenna-I [23] shared a single one channel, the antenna thus is not suitable for full-duplex operations. The proposed design in this paper has the separate channels for the dual-band operation, good integrated filtering function, and a low frequency ratio (f_H/f_L). Therefore, the proposed antenna has a higher level of systematic integration than the other antennas.

IV. CONCLUSION

In this paper, a compact (0.7λ × 0.7λ × 0.045λ) four-port DBDP antenna with highly integrated duplexing and filtering functions is proposed for the first time. By using the co-design concept, the dual-band duplexing operations in both ±45° polarizations are achieved simultaneously with a single radiation element. Such an integrated design could significantly reduce the volume, complexity and potential cost of the RF frontend of the base station while providing the improved frequency performance. The designing concept and analysis methods have been presented and discussed. The antenna was prototyped and tested and the measured results agree well with the simulations. The targeted specifications are fulfilled on the whole, except that the impedance bandwidths are slightly narrower than the specifications.

REFERENCES

[1] K.-L. Wong, *Compact and Broadband Microstrip Antennas*. Hoboken, NJ, USA: Wiley, 2002.

[2] D. M. Pozar and S. D. Targonski, "A shared-aperture dual-band dual-polarized microstrip array," *IEEE Trans. Antennas Propag.*, vol. 49, no. 2, pp. 150–157, Feb. 2001.

[3] K. M. Luk and H. Wong, "A new wideband unidirectional antenna element," *Int. J. Microw. Opt. Technol.*, vol. 1, no. 1, pp. 2098–2101, Jul. 2006.

[4] B. Q. Wu and K. M. Luk, "A broadband dual-polarized magneto-electric dipole antenna with simple feeds," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 60–63, 2009.

[5] S. Chen and K.-M. Luk, "A dual-mode wideband MIMO cube antenna with magneto-electric dipoles," *IEEE Trans. Antennas Propag.*, vol. 62, no. 12, pp. 5951–5959, Dec. 2014.

[6] Y. Gou, S. Yang, J. Li, and Z. Nie, "A compact dual-polarized printed dipole antenna with high isolation for wideband base station applications," *IEEE Trans. Antennas Propag.*, vol. 62, no. 8, pp. 4392–4395, Aug. 2014.

[7] S. Daoyi, J. J. Qian, H. Yang, and D. Fu, "A novel broadband polarization diversity antenna using a cross-pair of folded dipoles," *IEEE Antennas Wireless Propag. Lett.*, vol. 4, pp. 433–435, 2005.

[8] L. Y. Nie, X. Q. Lin , Y. J. Chen , J. Zhang , B. Wang , Z. Q. Yang, and Y. Fan "A low-profile coplanar dual-polarized and dual-band base station antenna array," *IEEE Trans. Antennas Propag.*, vol. 66, no. 12, pp. 6921–6929, Dec. 2018.

[9] Y. Luo, Q.-X. Chu, and D.-L. Wen, "A plus/minus 45 degree dual-polarized base-station antenna with enhanced cross-polarization discrimination via addition of four parasitic elements placed in a square contour," *IEEE Trans. Antennas Propag.*, vol. 64, no. 4, pp. 1514–1519, Apr. 2016.

[10] Y. Cui, R. Li, and P. Wang, "Novel dual-broadband planar antenna and its array for 2G/3G/LTE base stations," *IEEE Trans. Antennas Propag.*, vol. 61, no. 3, pp. 1132–1139, Mar. 2013.

[11] X. Li, R. W. Heath, Jr., K. Linehan, and R. Butler, "Metrocell antennas: The positive impact of a narrow vertical beamwidth and electrical downtilt," *IEEE Veh. Technol. Mag.*, vol. 10, no. 3, pp. 51–59, Sep. 2015.

[12] L. Zhao and K.-L. Wu, "A dual-band coupled resonator decoupling network for two coupled antennas," *IEEE Trans. Antennas Propag.*, vol. 63, no. 7, pp. 2843–2850, Jul. 2015.

[13] X.-Y. Zhang, D. Xue, L.-H. Ye, Y.-M. Pan, and Y. Zhang, "Compact dual-band dual-polarized interleaved two-beam array with stable radiation pattern based on filtering elements," *IEEE Trans. Antennas Propag.*, vol. 65, no. 9, pp. 4566–4575, Sep. 2017.

[14] Y. Liu, S. Wang, N. Li, J.-B. Wang, and J. Zhao, "A compact dual-band dual-polarized antenna with filtering structures for sub-6 GHz base station applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 10, pp. 1764–1768, Oct. 2018.

[15] Y. Zhang, X. Y. Zhang, L.-H. Ye, and Y.-M. Pan, "Dual-band base station array using filtering antenna elements for mutual coupling suppression," *IEEE Trans. Antennas Propag.*, vol. 64, no. 8, pp. 3423–3430, Aug. 2016.

[16] C.-X. Mao, S. Gao, Y. Wang, Q. Luo, and Q.-X. Chu, "A shared-aperture dual-band dual-polarized filtering-antenna-array with improved frequency response," *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 1836–1844, Apr. 2017.

[17] J.-F. Li, Z. N. Chen, D.-L. Wu, G. Zhang, and Y.-J. Wu, "Dual-beam filtering patch antennas for wireless communication application," *IEEE Trans. Antennas Propag.*, vol. 66, no. 7, pp. 3730–3734, Jul. 2018.

[18] H. Chu, C. Jin, J.-X. Chen, and Y.-X. Guo, "A 3-D millimeter-wave filtering antenna with high selectivity and low cross-polarization," *IEEE Trans. Antennas Propag.*, vol. 63, no. 5, pp. 2375–2380, May 2015.

[19] W. Duan, X. Y. Zhang, Y.-M. Pan, J.-X. Xu, and Q. Xue, "Dual-polarized filtering antenna with high selectivity and low cross polarization," *IEEE Trans. Antennas Propag.*, vol. 64, no. 10, pp. 4188–4196, Oct. 2016.

[20] C. X. Mao, S. Gao, Y. Wang, Z. Wang, F. Qin, B. Sanz, Q. X. Chu, "An integrated filtering antenna array with high selectivity and harmonics suppression," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 6, pp. 1798–1805, Jun. 2016.

[21] X. Y. Zhang, Y. Zhang, Y.-M. Pan, and W. Duan, "Low-profile dual-band filtering patch antenna and its application to LTE MIMO system," *IEEE Trans. Antennas Propag.*, vol. 65, no. 1, pp. 103–113, Jan. 2017.

[22] C. X. Mao, S. Gao, Y. Wang, F. Qin, and Q. X. Chu, "Compact highly integrated planar duplex antenna for wireless communications," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 7, pp. 2006–2013, Jul. 2016.

[23] C. X. Mao, S. Gao, Y. Liu, X. X. Yang, Z. Q. Cheng, and Y. L. Geng, "Integrated dual-band filtering/duplexing antennas," *IEEE Access*, vol. 6, pp. 8403–8411, 2018.

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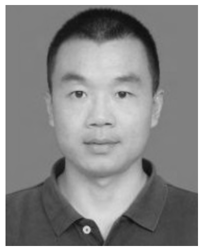

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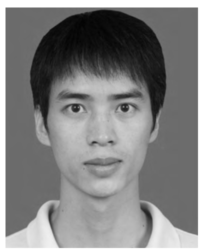

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